

## VIRTUAL ENVIRONMENT APPLICATION WITH PARTIAL GRAVITY SIMULATION

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### ABSTRACT

To support future manned missions to the surface of the moon and Mars and missions requiring manipulation of payloads and locomotion in space, a training facility is required to simulate the conditions of both partial and microgravity as compared to the gravity on Earth. A partial gravity simulator (Pogo), which uses pneumatic suspension, is being studied for use in virtual reality training. The Pogo maintains a constant partial gravity simulation with a variation of simulated body force between 2.2% and 10%, depending on the type of locomotion inputs. This paper is based on the concept and application of a virtual environment system with the Pogo.

The virtual environment system includes a head-mounted display and glove. The reality engine consists of a high-end SGI workstation and PC's which drive the Pogo's sensors and data acquisition hardware used for tracking and control. The tracking system discussed is a hybrid of magnetic and optical trackers which are being integrated for this application. Future upgrades are planned for the facility to further increase the sense of immersion it provides to the subjects training in the virtual environment.

### INTRODUCTION

Virtual Reality (VR), or Virtual Environment (VE), systems have come a long way in the past several years. Initially, users could only immerse themselves visually in an environment where their head movements were tracked mechanically. Today there are a variety of tracking options, besides mechanical methods, which do not encumber the user giving them greater freedom with natural motion. In

addition, gloves have become available which allow users to interact with virtual objects in their environment. Many researchers are working to include sensory feedback, such as temperature and pressure, through these gloves. Furthermore, three-dimensional audio systems are now available which allow users to hear spatialized sounds in their environment through headphones increasing the level of immersion the user has in the virtual environment. Researchers and end-users now have audio, visual, and some sensory feedback in their interactive virtual environments.

At NASA's Lyndon B. Johnson Space Center (JSC), research is being conducted towards increasing the level of sensory immersion in a virtual environment by merging present VR hardware capabilities with a partial gravity simulator. This application would allow users to interact within a virtual environment while physically experiencing microgravity to some degree. The purpose for providing partial gravity simulation on Earth is for crew safety. The more experience an astronaut has with microgravity as he or she prepares for a mission, the less the chances of risk or mishap that will occur during the actual mission.

Partial gravity simulation techniques will be described to some degree with greater detail provided on the Pogo partial gravity simulator. The concepts discussed will provide a better understanding of the significance and timeliness of the VE application. A description of the VE architecture that is being developed for the Pogo will follow with some mention of future plans underway. The conclusion will state the findings and status of the research

that has been completed as of the submission of this article (October 1994).

## **PARTIAL GRAVITY SIMULATION TECHNIQUES**

At present, NASA has two frequently utilized techniques for providing astronauts with a physical experience of microgravity. The first is through the KC-135. The KC-135 is a modified aircraft which allows a person to experience weightlessness or microgravity by flying parabolic trajectories. The second method is by using the Weightless Environment Training Facility, where suited astronauts are made neutrally buoyant underwater by attaching ballasts on their suits. These two methods serve their purpose for specific training applications, but they each have their advantages and disadvantages.

### **KC-135 Aircraft**

The KC-135 has the advantage of providing true zero-g or partial-g simulation. As the aircraft reaches its apogee and begins to descend, the crew can experience a wide range of microgravity depending on the slope of descent. In addition, the aircraft provides a comfortable shirt sleeve environment for studying the effects of microgravity on the crew.

Unfortunately, the simulation is limited by the amount of time an astronaut can execute a particular action. If zero-g conditions are desired, the total duration of simulation is approximately 30 seconds, of which only 20 seconds is available for useful data. If Lunar gravity, or 1/6-g is desired, 30 seconds is the period available to take data. If Martian gravity, or 3/8-g is desired, the useful period is about 40 seconds. The disadvantages due to the short duration of the simulation is obvious. In addition, there are restrictions due to the internal volume of the aircraft. A crew member is limited to a volume 79 in. high, 36 in. wide, and 247 in. long. Finally, the parabolic trajectory, which is executed repeatedly on a flight, can easily induce motion sickness. The KC-135 happens to be nicknamed the "Vomit Comet."

## **Weightless Environment Training Facility**

The Weightless Environment Training Facility, or WETF, simulates partial gravity using Archimedes principle applied to water buoyancy. Its advantages are the full range of degrees-of-freedom it offers in a fairly large volume without the need for mechanical support structures. The disadvantages include the resistance to body motion due to hydrodynamic drag and the limitations on training hardware that can be used due to the corrosive effects of the conditioned water. In addition, simulating lunar or planetary surfaces is very difficult and not practical in a water facility. Finally, the crew has the same dangers that divers must face anytime they remain submerged in the water.

Besides the above methods of microgravity simulation, there have been a number of suspension techniques (which will not be described here in detail) including inclined plane suspension, counterbalance suspension, bungee cord suspension, and pneumatic suspension. The partial gravity simulator which is being used for this research is called the Pogo, which uses pneumatic suspension.

## **THE POGO PARTIAL GRAVITY SIMULATOR**

The Pogo system is a combination of hardware salvaged from a partial gravity simulator used during the Apollo program and state-of-the-art data acquisition and control equipment added during current system development and testing efforts. Pogo consists of three major systems: (1) the vertical servo system; (2) the display and control system; and (3) the gimbal support system. The vertical servo system, shown in Figure 1, provides control of the pneumatic actuator by using servovalve amplifiers. The vertical servo system and the gimbal support system and their principles of operation will be described before presenting the research activities proposed for the virtual environment system integration with the Pogo.

## Vertical Servo System Description

The vertical servo system is the mechanism which applies a constant lifting force opposite in direction to the Earth's gravity vector. The vertical servo system consists of: (1) the vertical servo assembly; (2) the cylinder assembly; and (3) the piston rod assembly. Lifting force is provided by supplying the cylinder with pressurized air regulated by the vertical servo assembly. The available air supply to the vertical servo assembly has a maximum pressure of 120 psig (lbs. per sq. in. gage) or 134.7 psia (lbs. per sq. in. absolute) and a maximum flow rate of 367 scfm (standard cubic feet per minute).

## Gimbal Support System

The gimbal support assembly is the structure in which training participants are placed to provide the rotational degrees-of-freedom of pitch, roll and yaw. The gimbal support assembly is constructed of aluminum for the structural members and either nylon or kevlar webbing for the support straps. Kevlar is used due to its excellent strength-to-weight ratio and its high resistance to deflection or stretching. Minimal deflection is important because forces stored in the straps, due to elastic properties while deflecting under loaded conditions, will adversely affect the partial gravity simulation. Once a training participant is placed on the seat support and strapped into the chest harness, adjustments are made to insure the body center of gravity coincides with the pitch, roll and yaw axes of the gimbal. A full 360° rotational freedom is capable about the pitch and yaw axes, but the rotation about the roll axis is limited to +/-30°.

## Vertical Servo Flow System Description

Maintaining stability in pneumatic systems is a problem when designing closed loop pressure and flow controls. Harmonic oscillations or whistles can be generated, given certain flow conditions coupled with changing line diameters, nozzles and orifice restrictions when compressed air is transmitted. Such conditions are prevalent

in the vertical servo flow control system, which is shown schematically in Figure 2.

According to Burrows [3], "The main goal in designing a control system is to achieve adequate dynamic performance without the system becoming unstable." One of the design goals in developing a stable control system for the vertical servo is to determine the best combinations of supply pressure and flapper-nozzle control valve gap settings that result in stable performance of the two-stage mechanical amplification feedback of the Pogo vertical servo. The Pogo vertical servo is a pressure and flow regulating device in which the amplification is error actuated. To operate properly, the vertical servo needs to be a fast responding regulator, where the desired lift force from the piston/cylinder lifting actuator is maintained constant for a continuously varying input load at the end of the actuator.

The first step in developing a stable operating control system is to define the system. A control block diagram of the vertical servo flow control system is shown in Figure 3. The first stage of the vertical servo consists of the flapper-nozzle control valve, and the second stage consists of the intake and exhaust servovalves. An instantaneous change in pressure ( $P_{ao}$ ) in the cylinder, due to training participant motion, is compared to the desired input lifting pressure ( $P_{ai}$ ) for constant partial gravity simulation. The result of this comparison is the error signal ( $\epsilon$ ). The error is amplified by the flapper-nozzle control valve element ( $F_b$ ), which represents the influence of the bias spring force of the vertical servo. The flapper-nozzle controller in turn affects the back pressure ( $P_b$ ) in the intake and exhaust servovalves. The back pressure ( $P_b$ ) is considerably less than the control pressure ( $P_c$ ), due to the orifice restriction at the inlet to each servovalve control chamber. The servovalve amplifier acts as a second stage pressure regulating element, which further amplifies the error signal and supplies the required pressure change to the lifting cylinder to reduce the difference between ( $P_{ai}$ ) and ( $P_{ao}$ ).

The vertical servo acts basically as a two-way flow and pressure regulator. The main supply of air flow enters the intake of the valve chamber of the intake servovalve and is then diverted to two different directions. One direction is toward the inlet to the lifting cylinder and the other is toward the inlet to the exhaust servovalve. The amount of air flow going to either the cylinder or to the exhaust is proportional to the back pressure ( $P_b$ ), which varies according to the position of the flapper between the control nozzles. The error signal ( $\epsilon$ ) is directly proportional to the position of the flapper between the control nozzles.

### **VE Applications with Pogo**

The advantages of using a virtual environment with the Pogo is that visual and audio cues can be coupled with full body motion. This effect obviously increases the sense of immersion within the environment. In addition, one can easily change the virtual environment by loading the needed environment database into the reality engine allowing for various training scenarios to be exercised in one facility. Furthermore, the environment can be shared with other users who are utilizing the same database. Such a facility has great potential for space station assembly or extra-vehicular training. In addition, this would be an ideal facility for virtual training in Lunar or Martian environments.

The Mockup & Trainer Section and the PLAID Lab at JSC began collaborating on a concept study in July 1994, which has become focused on exploring hybrid tracking systems and delivering tracking information over an ethernet network to provide VE capabilities for the Pogo.

### **CURRENT VE SYSTEM ARCHITECTURE**

The hardware components that make up this particular VE system are all commercially available. The present VE hardware capabilities available on the market are adequate for studying this application and for determining the issues which will need to be resolved in order to materialize the

concept. Due to the large working volume of this facility (1 meter in width, 2 meters in height, and 10 meters in length) a hybrid system will be tested and evaluated to gather the subject's position information.

Two SGI Crimson workstations are currently being utilized in this system. The platform will soon be upgraded with an Onyx. Besides the graphical workstations, a PC is being used to transmit the I/O from a DC pulsed magnetic tracker and a right handed glove to the scene generator.

The software found in the PLAID Lab, the PLAID/VE version represents some of the most detailed and realistic VE models at JSC. The PLAID Lab has models of the Space Station, the Orbiter, and MIR, with both internal & external views. In addition, it has models of payloads that will fly on the Orbiter through the middle of 1996. The PLAID Lab also has 3-D models of the human body which can be calibrated to an individual's anthropometric characteristics (i.e. height, length of limbs, size, etc.). This model is also known as Jack<sup>TM</sup> to those who are familiar with this human factors analysis tool. Although Jack<sup>TM</sup> was conceptually born at JSC, the Center for Human Modeling and Simulation has devoted a great deal of work by developing Jack<sup>TM</sup> into a fully jointed human figure with real-time movement in three dimensions. EVA tools and foot restraints, which are used by Jack<sup>TM</sup>, are other items at the disposal of the user in the virtual environment.

The first step in the development of the Pogo VR software was to create a data pipeline to connect the Pogo workstation (an IBM PC running Microsoft DOS) to the PLAID Lab's SGI Crimson's. This pipeline would then allow the Pogo computer to send test-subject sensor data to the PLAID Lab computer, which could then generate a graphical image showing the training participant's position and orientation.

Since both the Pogo and PLAID computers were already connected via an ethernet network, the decision was made to implement the data pipeline using sockets.

Thus, the computers would cooperate to create a socket connection, which could then be read and written to byte by byte for sending and receiving data across the network. Sockets are native to UNIX, which made the development of the software for the PLAID Lab computer straightforward. The Pogo computer on the other hand required the purchase of third party programming libraries (from FTP Software, Inc.) to allow the use of sockets with DOS.

Since sensors had not yet been installed on the Pogo computer, the data pipeline software was tested using sensor data which had been recorded in the PLAID Lab. The Pogo computer's data pipeline software read the data from a file and then echoed it across the network. And as the PLAID Lab received the data, an image of a test subject was drawn and updated.

Work is currently underway to modify the Pogo's data pipeline software to read data from real-time sensors, which are now being installed on the Pogo computer.

### **Trackers**

Testing was conducted on the Pogo to determine the tracking capabilities and limitations of a magnetic tracker mounted on the spreader bar of Pogo's gimbal structure. The tracker was on loan at the time and the network data transfer described earlier was not available. Nevertheless, results show that this configuration produces accurate measurements for the head. However, as the distance from the transmitter to the sensors went beyond four feet, poor measurements were being generated. The problems were due to the ferrous materials in the gimbal's bearings which allow the subject to pitch, yaw, and roll. It was determined that additional work was required to reduce or eliminate the ferrous material in Pogo's gimbal to capture useful data with the magnetic tracker so that it could track both the head and hands of a subject in the gimbal.

As tracking solutions were being explored, an idea was developed to utilize two trackers, optical and magnetic, to provide

the position and orientation of the head in a large working volume. As it turns out, this idea has already been discussed among researchers such as Biocca [4]. Work is now underway in the PLAID Lab to integrate an optical tracking system with the magnetic tracking system. Essentially, the optical system will be tracking the magnetic transmitter. The relative coordinates of the magnetic tracker will then be determined by its position and orientation with respect to the optical system's point of reference. A demonstration of a passive optical tracking system has been set up to evaluate this scenario. Results will be presented at the 1994 ISMCR Workshop on Virtual Reality.

Although an optical tracking system which provides real-time position AND orientation is not commercially available, vendors are saying that this problem is being worked out and that such a system may be available in the first quarter of 1995. In order to obtain orientation information from current optical trackers, it is necessary to post-process the position data that is taken in real-time.

### **Concept VE System Architecture**

The VE system that may eventually be integrated with the Pogo is shown in Figure 4. PC's are planned to handle all of the I/O for tracking and sound. The number of PC's will have to be determined by the requirements of the various hardware trackers and sensors. The data from the gloves, body suit, and the magnetic tracker will be sent to a serial port in a PC which will then send the information over the ethernet to the scene generator. The latencies will occur at the PC's and at the scene generator. Latencies due to sending the information over the ethernet are not expected. If four serial lines transmit at 19.2k baud, which would equate to approximately 6 kilobytes/second with 25% overhead, this would still be well within the maximum throughput of ethernet, even with additional traffic. Once the information is shipped over the ethernet, latencies will occur as the information is received, reduced (processed), applied to the transformation matrices in the database, and then displayed. The amount of latency is minimal for the

current architecture. Only experimentation will be able to determine the amount of latency created by the addition of the other devices. The amount of acceptable latency will also, in turn, determine the maximum number of devices and sensors.

Electromechanical systems, such as the Cyberface 3™, are not being considered because of the limitations to movement and the range involved in the facility. Acoustic systems would be inaccurate in this application due to the amount of acoustical noise inherent in the Pogo and the reflective acoustics of the building which houses the facility. Finally, inertial tracking systems are not being considered because of the inability to recalibrate the individual markers needed, as the errors accumulate, to track the subjects entire body.

Although much work is left to be completed in order to determine the system described above, the VR hardware shown in Figure 4 is planned for integration. A left-handed CyberGlove™ is planned to become a part of the PLAID Lab's VR peripherals. In addition, the Flight Crew Support Division is receiving a Convolvotron™ for the development of spatialized communications during extra-vehicular activity (EVA) in space. Astronauts have great difficulty in determining where another EVA crew member is when they are not within view of the helmet's visor. The 3-D audio communications will assist the astronauts in locating each other as they work in space. The utilization of a body suit to track the entire body of a subject in the Pogo is also being considered. This would allow for the use of Jack™ within the environment where the user could actually look down and see their virtual body within the environment.

## CONCLUSION

The experimentation and research that has been conducted thus far has shown that this concept is feasible. The greatest technical hurdle to overcome is the tracking and the latencies of the system. Overhead due to software can be minimized through clever

programming to some degree, but hardware latencies will still have to be addressed.

Improvements in the Pogo itself are needed and are currently being addressed, but the application of a virtual environment with this facility will depend on the design and capabilities of the VE System. Overall system latencies will ultimately determine the amount of VR devices and sensors that can be integrated into the Pogo system. This is what is planned to be addressed in research and experimentation as training scenarios are developed for the astronauts.

## ACKNOWLEDGMENTS

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## REFERENCES

- [1] Johnson, H. I. and Trader, A. G., Pneumatic Amplifier Controls High Pressure Fluid Supply, NASA Tech Brief, Brief 71-10081, April 1971.
- [2] Ray, D. M., Partial Gravity Simulation Using A Pneumatic Actuator With Closed Loop Mechanical Amplification, NASA Technical Memorandum 104798, June 1994.
- [3] Burrows, C. R., Fluid Power Mechanisms, 1st ed., London: Van Nostrand Reinhold Co., 1972.
- [4] Biocca, Frank A., Hugh Applewhite and Kenneth Meyer, "A Survey of Position Trackers," Presence, MIT, Volume 1, Number 2, 1992, pp 173-200.
- [5] Gump, David, Virtual Reality Handbook: Products, Services & Resources, Pasha Publications inc., Arlington, Virginia, 1993.

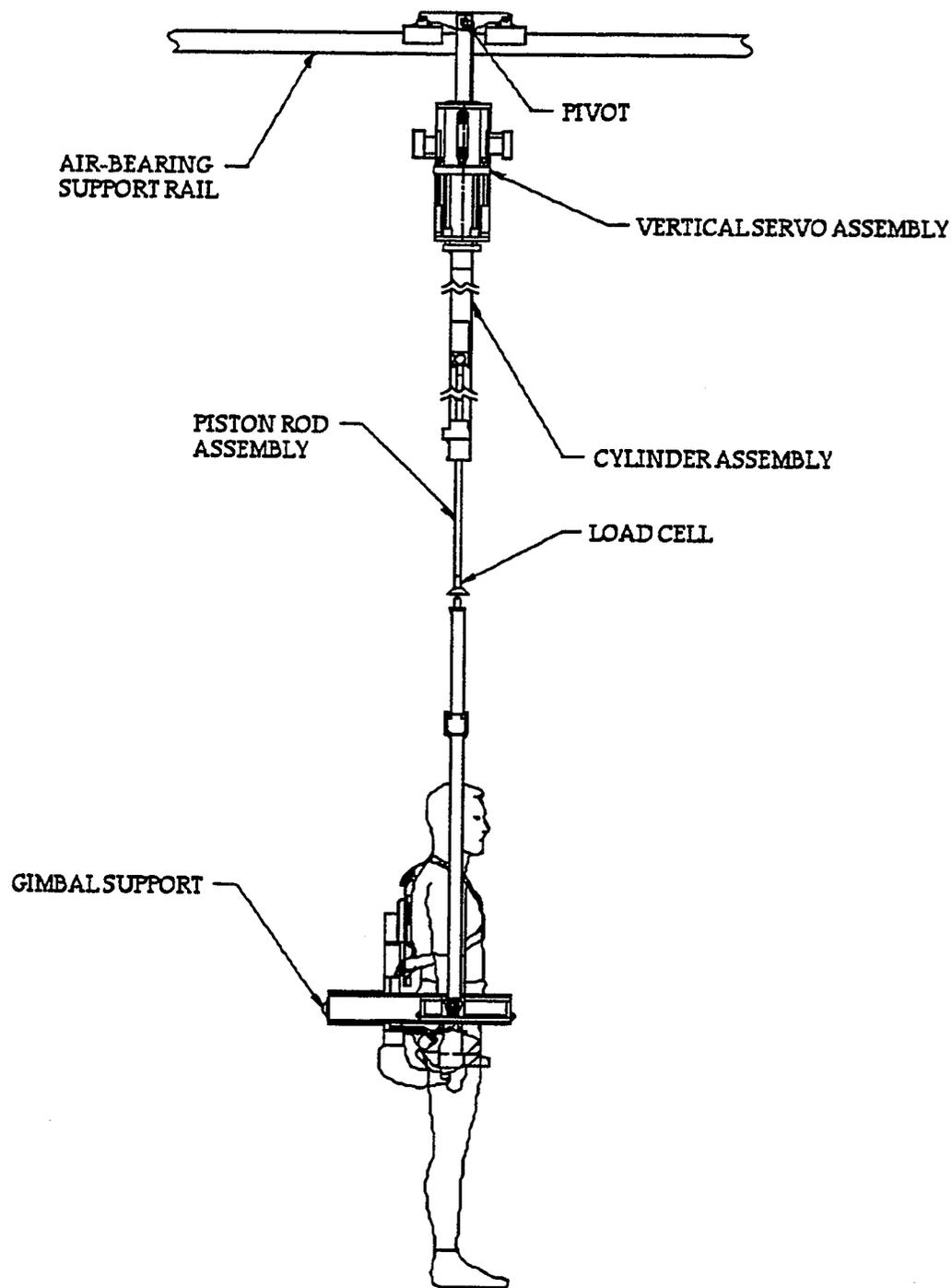


Figure 1. Pogo overall configuration. (Adapted from Trader and Johnson [1] and upgraded by Ray [2]. Gimbal drawn by B. Petty of the Johnson Engineering Corporation.

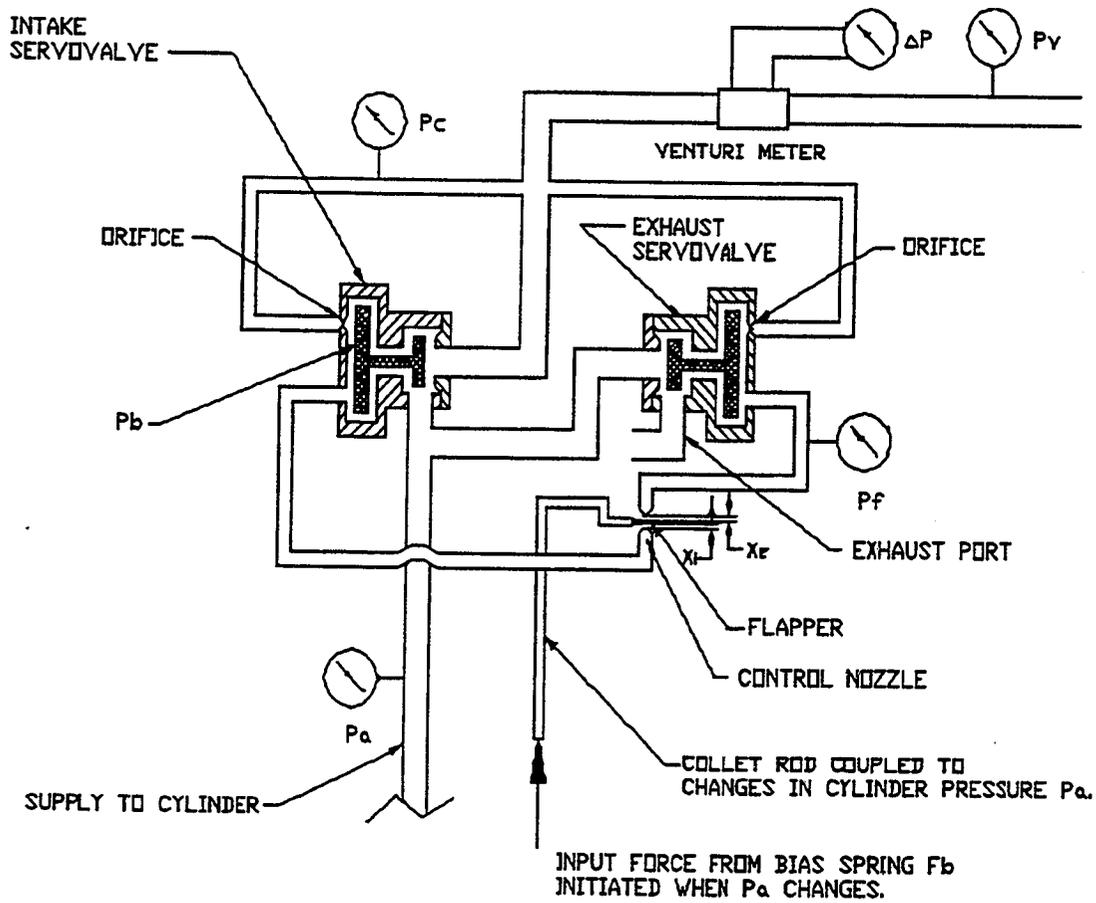
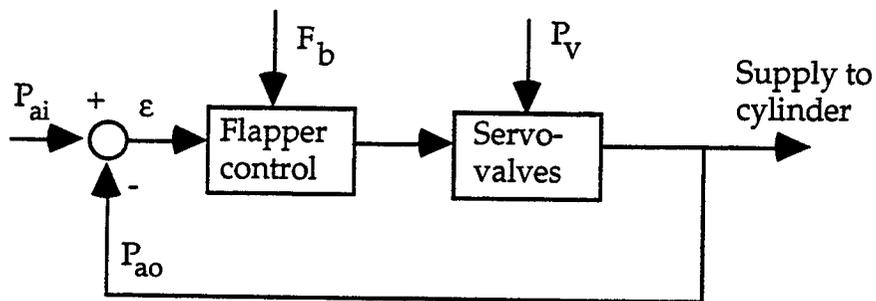


Figure 2. Vertical servo flow control system description.



$P_{ai}$  : Input lifting pressure to the cylinder.

$P_{ao}$  : Instantaneous output to the cylinder.

$\epsilon$  : Error signal.

$F_b$  : Bias spring input force which deflects the flapper.

$P_v$  : Pressure supply to vertical servo.

Figure 3. Control block diagram for the two-stage vertical servo.

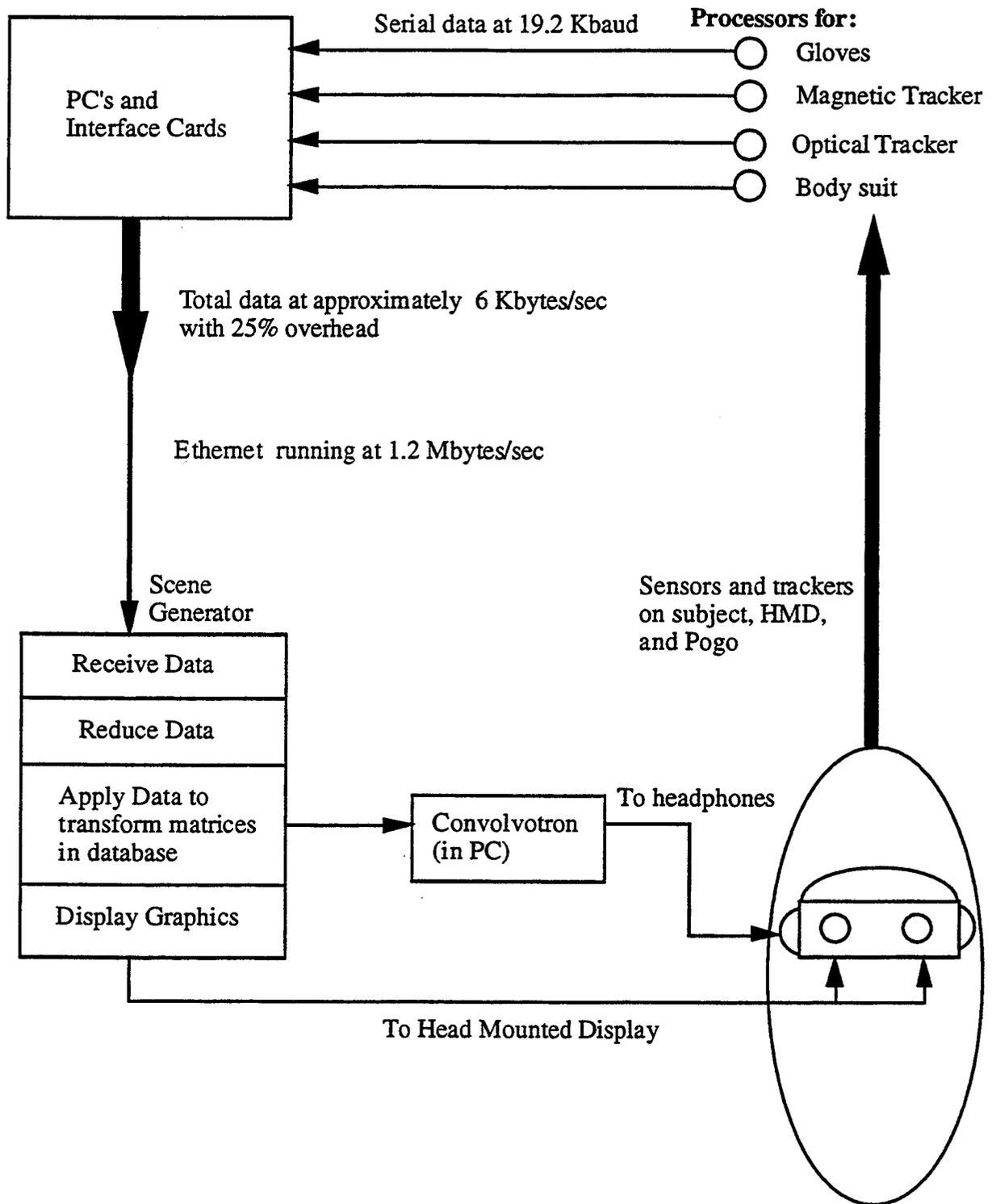


Figure 4. Concept VE System Architecture for Pogo